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Transition from rate-state friction to shear heating induced thermal pressurization during earthquakes

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1 Technical Abstract

We developed numerical methods to model thermal pressurization on faults with rate-state friction, including 1 dimensional fluid and heat transport. We model the nucleation stage of earthquakes from $\sim 10^{-9}$ m/s slip speed to dynamic slip rates (~ 1 m/s), by coupling rate and state friction equations to a Finite Difference mesh for the fluid and heat transport. Spatial grid refinement is implemented in the fault normal direction as required to maintain accuracy. We estimate the critical velocity at which thermal pressurization dominates the frictional weakening. We find that the critical velocity is much less than seismic slip-rates. Preliminary results indicate that the nucleation zone contracts in size substantially as thermal weakening becomes important.

2 Report

Thermal pressurization is a potential mechanism to explain the weakness of faults and the absence of a heat flow anomaly. *Segall and Rice* [2006] pointed out that thermal pressurization may affect seismic behavior even at the late nucleation of earthquakes before dynamic slip speeds are reached. In this study, we simulate thermal pressurization from the nucleation stage of earthquake on an infinitely thin fault plane. Our model combines evolution of the friction coefficient, elastic response of the surrounding medium, and buildup of pore pressure by thermal pressurization.

For the evolution of friction coefficient μ, rate- and state- dependent friction law (RS-law) [e.g., *Dietrich*, 1978]

$$\mu = \mu_0 + a \ln\left(\frac{v}{v_0}\right) + b \ln\left(\frac{\theta v_0}{d_c}\right) \tag{1}$$

is used in this study. Here, v is relative slip velocity between opposite sides of fault plane, θ is a state variable in RS-law. μ_0, a, b, v_0, and d_c are parameters of RS-law. Either of the commonly used state evolution laws are employed in our simulations.

We assume that the fault zone is infinitely thin and restricted to the fault plane ($y = 0$).

$$\frac{\partial T}{\partial t} = c_{th} \frac{\partial^2 T}{\partial y^2}. \tag{2}$$

c_{th} is thermal diffusivity. A boundary condition of thermal field is given by

$$\left.\frac{\partial T}{\partial y}\right|_{y=0} = -\frac{\tau v}{2\rho c_p c_{th}} \tag{3}$$

c_p is specific heat of the medium. At some distance from the fault we assume the temperature and pore pressure are unperturbed.

For uniform thermal and hydraulic properties *Rice* [2006] has shown that temperature and pore-pressure on the fault are linearly related, which implies that

$$\tau = \mu \left[\sigma_n - p_0 - \frac{\Lambda\sqrt{c_{th}}}{\sqrt{c_{th}} + \sqrt{c_{\text{hyd}}}} \left(T|_{y=0} - T_{\text{amb}} \right)\right] \tag{4}$$

c_{hyd} is hydraulic diffusivity. Thus we only need to compute the thermal field using the finite difference scheme.

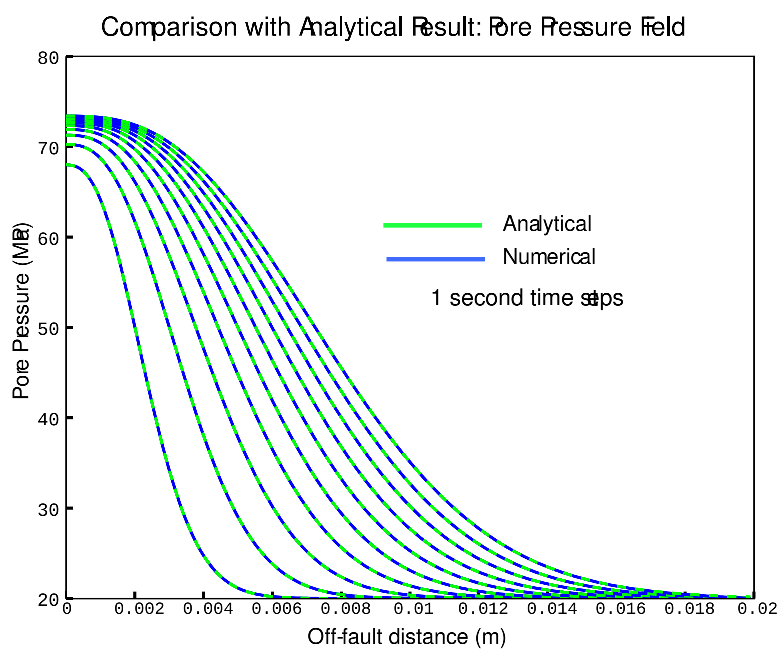

Figure 1: Comparison between finite difference and analytical pore-pressure distribution for the case of constant friction coefficient and constant slip speed.

In order to maintain numerical stability with explicit Finite Difference methods, the time step

Δt is limited by spatial grid interval Δy as,

$$c_{th}\Delta t \leq \frac{1}{2}(\Delta y)^2. \tag{5}$$

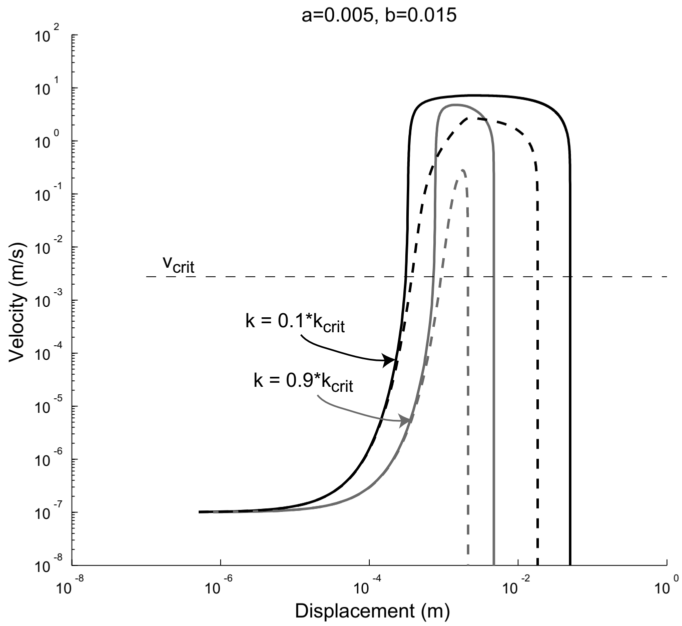

Figure 2: Log slip speed vs log displacement, comparing calculations with thermal pressurization (solid) with drained, constant pore-pressure results (dashed). Results shown for $k = 0.1k_{crit}$ and $k = 0.9k_{crit}$, where k_{crit} is the drained-isothermal critical stiffness.

We require a fine mesh during fast slip, in order to evaluate the steep thermal gradient around fault. On the other hand, a fine mesh requires extra computational time in the nucleation stage, where velocity and other parameters do not change abruptly. Therefore, we introduce remeshing technique, based on the thermal field around the fault plane. From the Taylor series expansion, spatial derivative in temperature at $y = 0$ is evaluated by

$$\begin{aligned} \left.\frac{\partial^2 T}{\partial y^2}\right|_{y=0} &= \frac{8T_1 - T_2 - 7T_0}{2(\Delta y)^2} - \frac{3}{\Delta y}\left.\frac{\partial T}{\partial y}\right|_{y=0} \\ &\quad + \frac{1}{6}\left.\frac{\partial^4 T}{\partial y^4}\right|_{y=0}(\Delta y)^2 + O\left[(\Delta y)^3\right]. \end{aligned} \tag{6}$$

T_i is temperature at $y = i\Delta y$. The second term is given by boundary condition. Third and fourth terms on the left hand side are neglected in the actual calculations. If higher order term become significant, this approximation is not appropriate. Thus, we check the ratio of third term (4-th order derivative) and first two terms in the left hand side at each time step to evaluate the validity of spatial grid interval. A criterion of remeshing is given by

$$\left|\frac{T_4 - 4T_3 + 6T_2 - 4T_1 + T_0}{3(8T_1 - T_2 - 7T_0 - 6\Delta y\, \partial T/\partial y|_{y=0}}\right| > C_r. \tag{7}$$

If this criterion is satisfied, we refine the mesh. We have verified the code by comparing to analytical results of [*Rice*, 2006] for constant slip speed and constant coefficient of friction (Figure 1).

Finite difference calculations with lumped parameter (spring-slider) elasticity, show that thermal effects become significant at even lower slip speeds than predicted by Segall and Rice [2006]. Figure 2 shows the slip speed as a function of displacement, with and without thermal pressurization, for two different stiffnesses. The critical slip speed v_{crit} as predicted by Segall and Rice [2006] is shown with the horizontal line. For $k = 0.1k_{crit}$, where k_{crit} is the drained-isothermal critical stiffness [Ruina, 1983], the drained solution departs from the coupled solution at slip rates an order of magnitude less than v_{crit}. The analytical result however, is predicated on the assumption that the nucleation zone size is near the critical size, such that the effective stiffness is only slightly less than the critical stiffness. In this case the drained solution departs from the full solution at slip rates two orders of magnitude less than v_{crit}. In both cases neglecting thermal pressurization greatly underestimates the net displacement and to a lesser degree the peak slip rate.

For reasonable parameters thermal pressurization results in a nearly complete stress drop (Figure 3). Because the stress is much lower during the period when large slip accumulates, the heat generation is vastly diminished relative to a fully drained case. However, without thermal pressurization the temperature would exceed the solidus of crustal rocks.

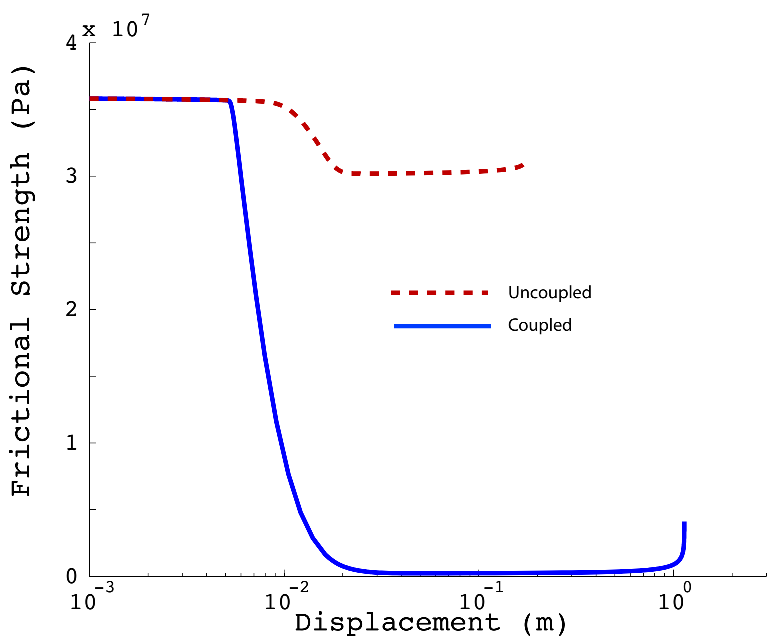

Figure 3: Frictional strength as a function of displacement, comparing the case with thermal pressurization (coupled) with the isothermal, drained (uncoupled case).

3 References Resulting From Funding

- T Matsuzawa, P Segall, Numerical simulation of the transition from frictional weakening to thermal pressurization during earthquakes, Eos Trans. AGU, 87(52), Fall Meet. Suppl., Abstract S42A-0, 2006.

- P. Segall and T. Matsuzawa, Earthquakes driven by thermal pressurization of pore fluids. Geological Society of America, Abstracts With Programs, Philadelphia Annual Meeting, 2006

- S. V. Schmitt, P. Segall, and T. Matsuzawa, Thermal Pressurization is Significant During Earthquake Nucleation, Before Seismic Slip, Eos Trans. AGU, 88(52), Fall Meet. Suppl., Abstract S12B-02, 2007.

Non-Technical Abstract

As faults in the earth slip, frictional heat is generated. It has long been known that the temperature anomaly near the San Andreas fault is much less than predicted based on standard estimates of frictional properties. One mechanism to explain this, is that faults become very weak during earthquakes, drastically diminishing the frictional heat production. The pores of fault zone rocks are known to be saturated with aqueous fluids, and the thermal expansivity of these fluids is much greater than that of rock that hosts them. Thus as frictional heat is generated the pressure of these pore-fluids will increase, thereby reducing the frictional resistance to further slip. We have developed numerical methods for simulating this "thermal pressurization" process and found that it becomes important much earlier in the nucleation of crustal earthquakes than was commonly believed. This suggests that thermal weakening may dominate the physics of fast earthquake-slip. Our simulations show that nucleation zones tend to contract after thermal weakening, which means that detecting precursory deformation will be more difficult than previously thought.